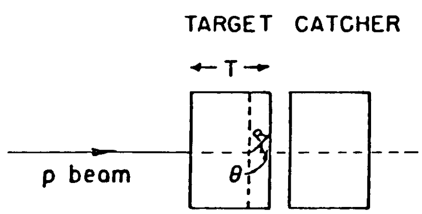
RECOIL RANGES OF NUCLEI PRODUCED IN PROTON-INDUCED REACTIONS

J. Jastrzebski,* H. Karwowski, M. Sadler,** and P.P. Singh

The energy with which various nuclei, produced in a nuclear reaction, recoil depends dramatically on the reaction mechanism which leads to their production. For example, the recoil energy $E_R(CN)$ of the compound nucleus formed after capture of a projectile with kinetic energy $E_p$ and of mass $A_p$ by target of mass $A_t$, given by $E_R(CN) = A_pA_TE_p/(A_p + A_T)^2$, may be as much as a factor of ten larger than the recoil energy of a nucleus produced by the same projectile and target combination but through a direct reaction such as inelastic scattering or the like. Further, nuclei which are produced following nucleon evaporation from some heavier nucleus must have the recoiling characteristics which are similar to that of their parent nucleus, except for some modification resulting from the evaporation. Thus study of recoil ranges can give an important clue towards the mechanism with which various nuclei are produced in an inclusive reaction.

The experimental method used in measuring the recoil ranges of the residual nuclei is schematically depicted in Fig. 1. If R is the average range and $\theta_R$ is the average recoiling angle of the nuclei produced in the reactions induced by incident protons in the target, then only those nuclei which are produced in the last segment of the target, R cos $\theta_r$ in thickness, will be able to get out into the catcher foil. If it is assumed that the nuclei are produced uniformly throughout the




$$R\cos\theta = \frac{A_C}{A_C + A_T}\,T$$

$A_C$ = ACTIVITY IN CATCHER

$A_T$ = ACTIVITY IN TARGET

R = RECOIL RANGE

$\theta$ = RECOIL ANGLE

T = TARGET THICKNESS

Figure 1

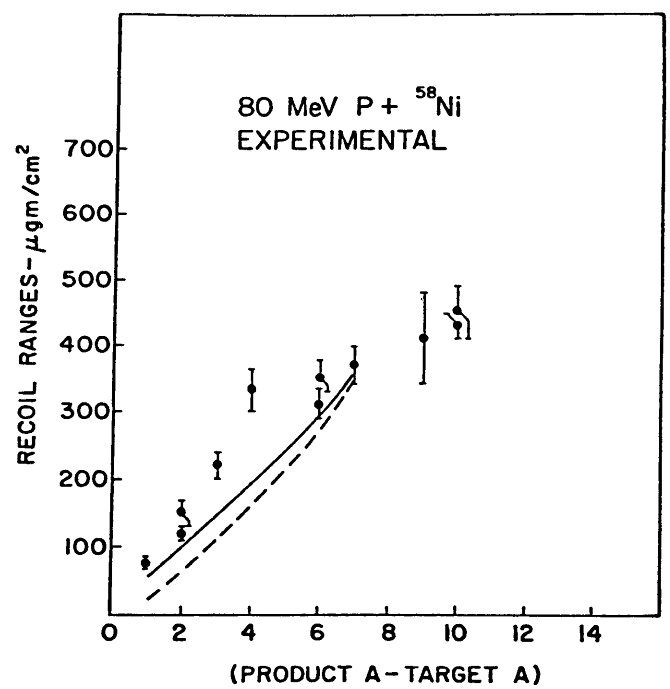



Figure 2

target, a reasonable assumption for the target thickness of 1-3 mg/cm$^2$ employed, then the ratio of the activity measured in the catcher to the total activity times the target thickness T is a good measure of the component of R along the beam direction. These measurements have been made with $^{58}$Ni targets at 80, 153 and 164 MeV and for $^{62}$Ni at 80, 136, 153 and 164 MeV. The results for $^{58}$Ni at 80 MeV and for $^{62}$Ni at 153 MeV are illustrated in Figs. 2 and 3 respectively.

The observed ranges vary, almost linearly, from about 50 μg/cm$^2$ for nuclei close to the target mass to about 700 μg/cm$^2$ for the nucleus farthest from the target at 153 bombarding energy. At 80 MeV the increase in the observed ranges with the number of nucleons removed from the target, ΔA is similar though perhaps a little slower for larger values of ΔA. It is instructive to compare the observed ranges for each nucleus with the range of the corresponding compound nucleus (referred to as $R_{CN}$ hereafter). For 80 MeV protons on $^{58}$Ni $R_{CN}$ (80 MeV) is equal to 370 μg/cm$^2$ for $^{59}$Cu and for 153 MeV protons on $^{62}$Ni $R_{CN}$ (153 MeV) is equal to 600 μg/cm$^2$ for $^{63}$Cu. Note (See Fig. 4) that $R_{CN}$ is close to the values of observed ranges only for the lightest of the nuclei at the two energies. The evaporation of nucleons tends to slightly increase the recoil energy, on the average, and the recoil ranges. However, these changes are expected to be relatively small and should not affect the discussion of these results significantly.

From the fact that the ranges of most nuclei are considerably less than $R_{CN}$, it can be concluded that none of these nuclei, except perhaps the lightest of the observed nuclei, were formed from the decay of the CN (i.e. the target + the projectile). The extremely small range of nuclei near the target mass imply that these nuclei were produced in processes in which

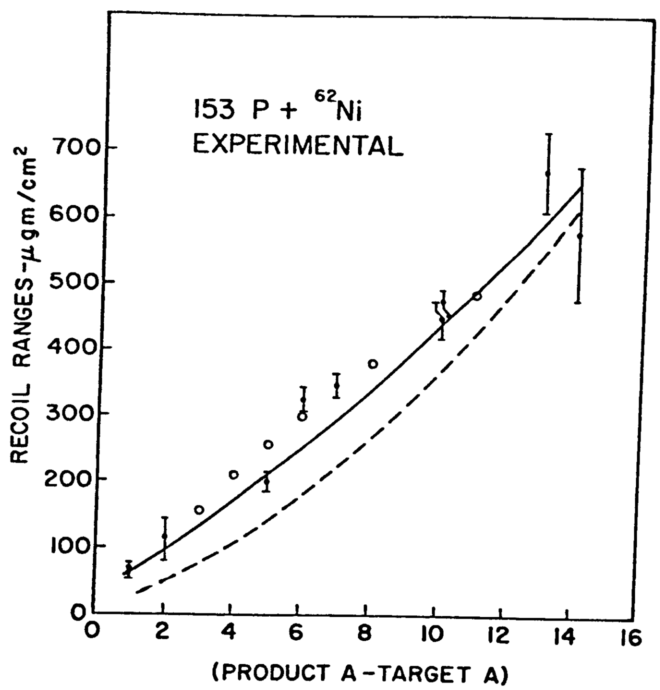



Figure 3

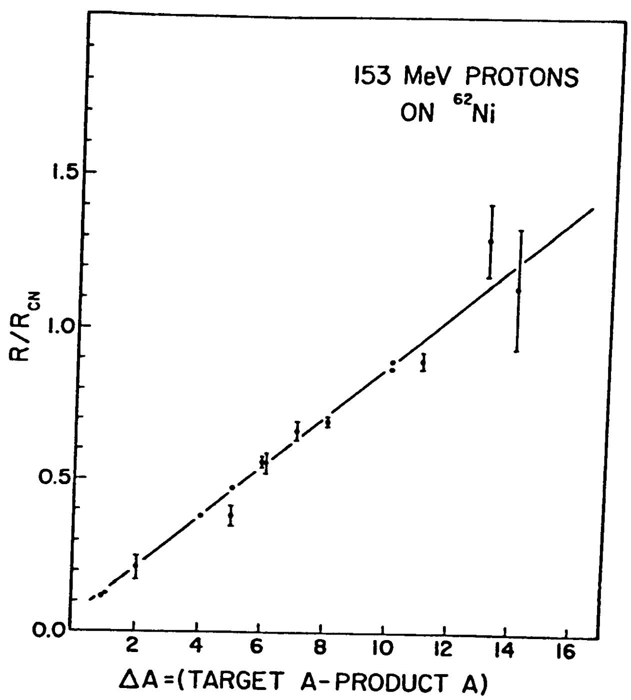



Figure 4

most of the incident momentum and energy is taken away by the emitted particles, a characteristic of the pre-equilibrium interactions. Increasing values of the recoil range with $\Delta A$ implies that the corresponding nuclei are produced in events in which a progressively smaller fraction of the incident energy is carried out by the emitted particles. The picture of the proton-nucleus interactions that emerges from the systematics of the observed ranges is that as the incident nucleon interacts with the target nucleons a number of residual nuclei $A_1$, $A_1$-1, -- (following the emission of some of the nucleons involved in the interaction) are left with a broad range of energy deposited as a consequence of those nucleons which are not able to escape from the nucleus. Most of the final products are produced following evaporation of nucleons from these parent nuclei. Since it takes 10 MeV of excitation energy to evaporate a nucleon, lighter final products are produced from successively higher excitations of the parent nuclei. Further, because evaporation does not substantially change the recoil energies[2] the final product nuclei, the daughters, shall be recoiling with the same energy as that of the parents.

Semi-quantitatively speaking, assume that a product of mass $A_t$-$\Delta A$, where $A_t$ is the target mass and $\Delta A$ is the number of nucleons evaporated, is formed from a parent of mass Ap at an excitation $E^*$. Then to a good approximation, in analogy with the capture reactions, its recoil energy $E_R$ is equal to $\frac{(A_p \cdot A_t)E_d}{(A_p + A_t)^2}$, where $E_d$ is the energy deposited in the nucleus as a consequence of the interaction. From the conservation of energy it is obvious that $E_d \equiv E_{in} - E_{out} = E^* + Q \overset{\sim}{\sim} 10\ \Delta A$. Here Q has been ignored in comparison with $E^*$ and the latter is equated to 10 $\Delta A$ utilizing the fact that it takes 10 MeV of excitation to evaporate one nucleon. The recoil range R is related[3,4] to the recoil energy $E_R$ as $R = kE^m$, where k is a constant depending upon the properties of the medium and the exponent m is unity for $E_R$ less than about 1 MeV and decreases to 1/2 for $E_R$ greater than 35 MeV. Thus, substituting for $\dot{E}$ one obtains that $R \approx k\ 10^m(\Delta A)^m$ or $R \approx 10k\ \Delta A$ since m is close to unity for recoil energies encountered in this study. It is interesting that this simple picture is able to predict the observed linear behavior of R with $\Delta A$.

A more quantitative accounting of the observed ranges can be attempted in terms of the recoil energies of the parent nuclei, $A_t$+1, $A_t$, $A_t$-1, --- at appropriate excitation energy, which leads to the production of particular daughter nuclei of mass $A_t$+1-$\Delta A$ by using the recoil energies and recoil angles calculated in terms of the cascade model.[5] The calculated ranges and their projections along the incident direction are shown as solid and dashed lines, respectively, in Figs. 2 and 3. Though the projected ranges given by the model are consistently lower than the observed ranges, their magnitude and dependence with $\Delta A$ is not very far from reality. It is hoped that when the kick given by the evaporation is taken into account that the remaining discrepancy may also disappear.

Slight disagreement not withstanding, it is very impressive that from the magnitudes and trends of measured ranges with ΔA one can conclude (a) that all final products are produced as a consequence of a few quasi-free interactions among the incident nucleon and the target nucleons and (b) that product nuclei which are many nucleons removed from the nuclei that are actually produced in the pre-equilibrium phase remember their parentage at least in so far as their recoil energies are concerned.

*Present address: INR, Swierk, Poland
**Present address: Department of Physics, UCLA, Los Angeles, CA 90024

1) See IUCF Technical and Scientific Report, 1977.

2) Winsberg, L. and Alexander, J.M., Phys. Rev. 121 (1961) 518.

3) Northcliffe, L.C. and Schilling, R.F., Nuclear data Tables A7 (1970) 233.

4) Lindhard, J. and Scharff, M., Phys. Rev. 124 (1961) 128.

5) M. Sadler, et al., this report, p. 124.